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Optimization design of non-coplanar target for pose measurement with monocular vision system

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ABSTRACT

In monocular vision system, non-coplanar target is extensively used for pose measurement. However, it remains a subject to be settled how to design and select the target parameters. This article proposes an optimized design method for non-coplanar target parameters to ensure that the monocular vision measuring system can attain optimal pose measurement accuracy. Firstly, a monocular-vision pose measurement model is established covering non-coplanar target parameters, and a pose measurement error model is deduced. On this basis, an objective function is put forward for optimizing the design of non-coplanar target parameters. Finally, simulations are conducted and the results verify the correctness of pose measurement error model and the effectiveness of the optimized design of target parameters.

1. Introduction

In recent years, pose measurement based on vision system has become a research focus [1–5]. The vision systems fall into two major categories:monocular vision [1–3] and binocular vision [4,5]. In which, the monocular vision system has many advantages such as simple structure and large field of view (FOV) for measurement, but its measurement accuracy is lower than that of the binocular vision system, especially for measurement of depth, where a large error may exist. At the same time, there is accuracy disparity between vision systems and traditional methods, such as laser tracker. In order to improve the vision measurement accuracy, the past researches were concentrated on camera calibration [6–8] and subpixel location technique [9,10] and resulted in many well-proven and practical methods. Besides, for binocular vision measurement, the accuracy can be improved by modifying the system configurations, such as the placement [11–14], effective FOV [15] and baseline length [16] of two cameras. However, for monocular vision measurement, its typical research subject is PnP problem [17,18]. PnP refers to a method to determine the pose of an object by the correlations of n sets of known space points and their image points of the object. If $n < 6$, there will be multiple solutions for above problem. And if $n \geq 6$, there will be a unique solution for the pose measurement provided that these n space points are non-coplanar.

To satisfy the requirements of subpixel location, non-coplanar target is usually placed on the surface of object [19–25] to be measured in vision system and used as measurement target. The non-coplanar target usually consists of several feature points and the different relative locations of the feature points represent different non-coplanar target parameters. The optimization design of non-coplanar target parameters will offer important theoretical and application value provided that it can improve the pose measurement accuracy of vision system. This article proposes an optimization design method for

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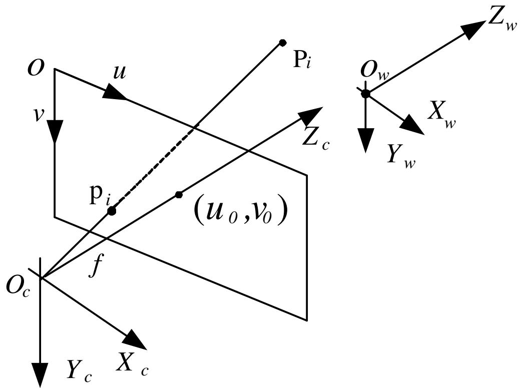

Fig. 1. Sketch of imaging correlation of feature points.

parameters of non-coplanar targets (feature points $n \geq 6$) to improve the pose measurement accuracy. That is, to optimize the design of non-coplanar target parameters based on pose measurement model and error transferring model of the object.

2. Pose measurement model with target parameters

Non-coplanar target is a geometry consisting of several feature points. In monocular vision pose measuring system, the non-coplanar target is placed on the surface of the object, and a unique solution can be ensured for the pose measurement if the target consists of 6 or more feature points. The pose to be measured can be expressed by the rotation matrix $R = (r_{ij})_{3\times3}$and the translation vector$(t_x, t_y, t_z)^T$, while the target parameters will be the three-dimensional coordinates $P_i = (X_{wi}, Y_{wi}, Z_{wi})^T (i \geq 6)$of various feature points in the world coordinate system.

Refer to Fig. 1 for the imaging correlation of feature points. Where, $O_cX_cY_cZ_c$is the camera coordinate system, $O_wX_wY_wZ_w$is the world coordinate system, $Ouv$is the image pixel coordinate system, $P_i$is a feature point with target parameter ($P_i = (X_{wi}, Y_{wi}, Z_{wi})^T$) and corresponding image point ($p_i = (u_i, v_i)^T$)$f$is the focal length of camera, and $(u_0, v_0)$is the principal point of camera.

In the perspective projection model, for a certain feature point, its parameter $P_i = (X_{wi}, Y_{wi}, Z_{wi})^T (i \geq 6)$and image point $p_i = (u_i, v_i)^T$satisfy a collinear equation, i.e.

$$\begin{cases} (u_i - u_0) \cdot dx = f \cdot \dfrac{r_{11}X_{wi} + r_{12}Y_{wi} + r_{13}Z_{wi} + t_x}{r_{31}X_{wi} + r_{32}Y_{wi} + r_{33}Z_{wi} + t_z} \\ (v_i - v_0) \cdot dy = f \cdot \dfrac{r_{21}X_{wi} + r_{22}Y_{wi} + r_{23}Z_{wi} + t_y}{r_{31}X_{wi} + r_{32}Y_{wi} + r_{33}Z_{wi} + t_z} \end{cases} (i \geq 6) \tag{1}$$

Where, $dx$and $dy$are the pixel sizes of the image in two directions.

By expansion, Eq. (1) will be

$$\begin{cases} fX_{wi}r_{11} + fY_{wi}r_{12} + fZ_{wi}r_{13} + ft_x - dx(u_i - u_0)X_{wi}r_{31} - dx(u_i - u_0)Y_{wi}r_{32} - dx(u_i - u_0)Z_{wi}r_{33} = dx(u_i - u_0)t_z \\ fX_{wi}r_{21} + fY_{wi}r_{22} + fZ_{wi}r_{23} + ft_y - dy(v_i - v_0)X_{wi}r_{31} - dy(v_i - v_0)Y_{wi}r_{32} - dy(v_i - v_0)Z_{wi}r_{33} = dy(v_i - v_0)t_z \end{cases} (i \geq 6) \tag{2}$$

Divided by $t_z$at both sides of the equation, it will be denoted as follow matrix:

$$AX = B \tag{3}$$

Where,$A = \begin{bmatrix} fX_{w1} & fY_{w1} & fZ_{w1} & 0 & 0 & 0 & -dx(u_1 - u_0)X_{w1} & -dx(u_1 - u_0)Y_{w1} & -dx(u_1 - u_0)Z_{w1} & f & 0 \\ 0 & 0 & 0 & fX_{w1} & fY_{w1} & fZ_{w1} & -dy(v_1 - v_0)X_{w1} & -dy(v_1 - v_0)Y_{w1} & -dy(v_1 - v_0)Z_{w1} & 0 & f \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ fX_{wn} & fY_{wn} & fZ_{wn} & 0 & 0 & 0 & -dx(u_n - u_0)X_{wn} & -dx(u_n - u_0)Y_{wn} & -dx(u_n - u_0)Z_{wn} & f & 0 \\ 0 & 0 & 0 & fX_{wn} & fY_{wn} & fZ_{wn} & -dy(v_n - v_0)X_{wn} & -dy(v_n - v_0)Y_{wn} & -dy(v_n - v_0)Z_{wn} & 0 & f \end{bmatrix}$;

$$X = (r_{11}/t_z, r_{12}/t_z, r_{13}/t_z, r_{21}/t_z, r_{22}/t_z, r_{23}/t_z, r_{31}/t_z, r_{32}/t_z, r_{33}/t_z, t_x/t_z, t_y/t_z)^T;$$

$$\mathrm{B} = (\mathrm{dx}(u_1 - u_0), \mathrm{dy}(v_1 - v_0), \cdots, \mathrm{dx}(u_n - u_0), \mathrm{dy}(v_n - v_0))^T (n \geq 6)$$

Set the element of X as $x_i (1 \leq i \leq 11)$.

The solution of Eq. (3) in the least squares will be

$$X = (A^T A)^{-1} A^T B \tag{4}$$